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Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling

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Abstract

Following a brief review of related literature, the paper outlines experimental results following finish turning of Inconel 718 using low concentration PCBN inserts. Testing utilised a modified L_{36} Taguchi fractional factorial orthogonal array which evaluated the effects of tool insert shape/geometry (round, C-type), tool edge preparation (extra honed, chamfered & honed), fluid pressure (10, 100bar), tool coating (uncoated, TiAlN+TiN), cutting speed (150, 300, 450m/min) and feed rate (0.05, 0.10, 0.20mm/rev) at a constant depth of cut of 0.2mm. At the lowest cutting speed (150m/min), average tool life using the round insert was approximately 5 times longer in comparison to the C-type tool, with severe grooving and built up edge (BUE) formation observed on wear scar micrographs in all experiments with the latter. As cutting speed was increased to 300m/min, the presence of grooving and BUE diminished, leading to comparable performance between the C-type and round tools. When turning at 450m/min however, several instances of catastrophic insert fracture occurred and tool life did not exceed 3.5mins, irrespective of the other parameters/conditions used. Adhesion of workpiece material on tool cutting edges was prevalent over the range of parameters tested with abrasion typically the primary mechanism causing insert wear.

Keywords: Turning; PCBN; superalloy; wear

1. Introduction

Carbide tooling is generally recommended for the machining of advanced nickel based superalloys such as Inconel 718 due to its good balance of fracture toughness and resistance to thermal shocks. Despite previous shortcomings in relation to processing speed, developments in grades and multi-layer coatings over the past decade have enabled cutting velocities approaching ~100m/min in finishing operations [1, 2]. From a ceramics tooling standpoint, mainstream alumina and mixed alumina products offer little or no benefit, as they suffer rapid degradation from a variety of associated tool wear mechanisms. Additionally, even silicon nitride and whisker reinforced products, although able in some cases to provide substantial productivity gains over carbide with specific alloys [3, 4], continue to remain constrained to roughing operations in aeroengine production. This is also currently true of polycrystalline cubic boron nitride (PCBN) use, in part a consequence of commercial factors, although technical limitations also preclude its application with the full spectrum of superalloys. More recently however, the use of coated PCBN tools allied with appropriate tooling configurations and processing

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methods has highlighted the potential for a step change in productivity in key areas such as disc fabrication.

PCBN cutting tools have traditionally been employed in hard part machining for ferrous based workpiece materials with hardness's of 50-70HRC, and are capable of generating surface roughness of ~0.2µm Ra using standard machine tools. Published research on using PCBN for the machining of nickel based superalloys has almost exclusively involved Inconel 718, with one of the earliest investigations being carried out by Focke et al. [5], who evaluated the performance of Borazon-BZN inserts when turning at 52 and 182m/min at a constant feed rate of 0.2mm/rev and depth of cut of 2.54mm. When cutting at the higher speed level, the tool exhibited ~20% lower flank wear after 4mins of machining. In a later study, Richards et al. [6] compared the performance of BZN against Sialon, SiC whisker reinforced alumina and carbide tooling at higher operating parameters of 120 to 250m/min, 0.3mm/rev feed rate and 2mm depth of cut. Tool life was seen to drop from 11mins to ~1min as cutting speed was increased, while all tools failed from depth of cut notching (notch wear localised at the depth of cut line) with the exception of the SiC whisker reinforced alumina, which showed uniform flank wear. Shintani et al. [7] examined the influence of binder composition (TiC, TiN and Co) in PCBN tooling when turning Inconel 718 at cutting speeds ranging from 60 to 240m/min while keeping the feed rate (0.1mm/rev) and depth of cut (0.1mm) fixed. Maximum tool life was obtained between 120 and 180m/min for all three tools, with the TiN binder giving the best performance due to its superior resistance to chemical diffusion.

The effect of PCBN cutting edge preparation when turning Inconel 718 under high cutting speed conditions (up to 1250m/min) was studied by Uhlmann and Ederer [8], who reported that a range of between 400–600m/min was recommended to minimise flank wear and cutting force levels. They also found that un-chamfered inserts were generally preferred over chamfered tool edges, as the former exhibited ~50% higher tool life and ~20% lower cutting forces when machining at 600m/min. Similar trends were observed by Pawade et al. [9], where the magnitude of cutting forces was up to 6 times lower when machining at 475m/min as opposed to 125m/min, due to greater softening of the workpiece at higher cutting speeds.

Coelho et al. [10] reported that severe depth of cut notching was the primary wear mode when finish turning Inconel 718 at 500m/min cutting speed, 0.1mm/rev feed rate and 0.35mm depth of cut using PCBN tools. Notch wear was also observed on the secondary cutting edge while flank wear progression was rapid and reached 300-350µm after a machined length of 185mm. Costes et al. [11] investigated the effect of CBN content, grain size and binder type on tool life and associated wear mechanisms. They found that high concentration CBN inserts (above 80%) only produced an average tool life of 2.8mins, but this increased by almost 4-fold (9.6mins) when utilising products with low CBN content (below 60%). This was mainly due to the greater adhesion and diffusion wear occurring in the former, as a result of the lower chemical stability associated with tools having a high percentage volume of CBN. More recently, work by Zhou et al. [12] showed that use of TiN coated PCBN tooling resulted in ~20% higher tool life compared to equivalent uncoated inserts when machining Inconel 718 at 250m/min. However, as the cutting speed was increased to 300 and 350m/min, no significant performance benefits accrued due to rapid oxidation of the coating layer.

2. Experimental work

The workpiece material used in all tests was Inconel 718 nickel based superalloy in the solution treated and aged condition with a nominal bulk hardness of ~46 HRC. This was delivered in the form of 4 cylindrical bars, each with a diameter and length of 90 and 122mm respectively. The cutting tools utilised were low concentration grade PCBN inserts (50% CBN content) with 2µm grain size and TiC ceramic binder phase. Two different geometries were evaluated involving 80˚ rhomboid (C-type) and round inserts corresponding to ISO designations of CNGA120412 and RCMW10T300 respectively. The C-type inserts were held in a toolholder with product code PCLNR2525M12JET, which resulted in tool cutting edge angle of 95˚, inclination and normal rake angles of -6˚ as well as a positive clearance of 6˚. Similarly, the round tools were clamped in a SRSCR2525M10JET toolholder providing a cutting configuration of 45˚ tool cutting edge angle, 0˚ inclination and normal rake angle together with a positive clearance of 7˚. Both toolholders were equipped with the patented Jetstream system of fluid inducers placed above the inserts to allow coolant to be aimed directly into the tool-chip interface. Evaluation of insert cutting edge preparation involved tools with an extra honed (25µm hone radius; designated as E25) and a chamfered plus honed (25° x 0.15mm chamfer + 15µm hone radius; coded as S) finish, see Fig. 1. In addition, half were supplied with a 1.5µm thick bi-layer coating comprising (Ti,Al)N (1µm) + TiN (0.5µm).

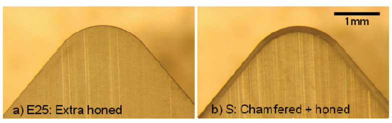

Fig. 1. Example of; (a) E25 and b) S type cutting edge preparation

The experiments were conducted on a MHP MT-80 CNC turning centre with a 30kW spindle motor having a maximum rotational speed of 3000rpm. Cutting force components were recorded using a Kistler 9257A, 3-component piezoelectric platform dynamometer (linked to charge amplifiers) connected to a PC running Dynaware software. A standard fixture was utilised to secure the cutting tool onto the dynamometer, which was in turn mounted on the lathe tool turret using a bespoke jig, see Fig. 2. The tool life criterion was a maximum flank wear of 300µm or notch wear of 600µm, in accordance with the ISO-3685 standard. Flank wear was measured at regular intervals using a Wild optical microscope fitted with 0.001mm resolution digital micrometers on an XY platform. Worn inserts were subsequently examined under a JEOL 6060 scanning electron microscope (SEM) to identify wear mechanisms. The cutting fluid employed was a water based emulsion containing 9-10% of soluble oil, which was supplied at pressure levels of either 10 (~ 6.5l/min) or 100 bar (~ 24l/min flow rate) respectively.

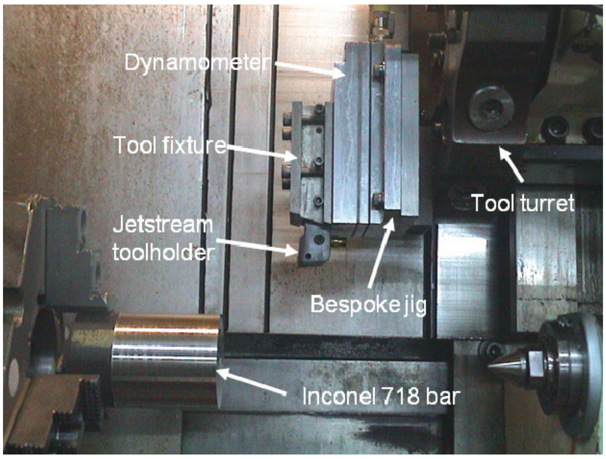

Fig. 2: Experimental set-up on MHP-CNC lathe

Due to the relatively large number of variable factors and levels specified together with limitations on workpiece material availability, a modified Taguchi fractional factorial design (L_{36} orthogonal array) comprising 36 runs was employed, see Table 1. This dramatically minimised the number of tests compared to a full factorial configuration, which would have entailed 144 trials. The depth of cut was kept constant at 0.2mm. Statistical analysis involving main effects plots and analysis of variance (ANOVA) was used to identify the significant factors/levels affecting tool life. Associated percentage contributions (PCR's) were calculated.

Table 1. Modified L_{36} Taguchi orthogonal array

Test	Insert shape	Edge prep.	Fluid pressure (*bar*)	Surface condition	Cutting speed (*m/min*)	Feed rate (*mm/rev*)
1	Round	E25	10	Uncoated	150	0.05
2	Round	E25	10	Uncoated	300	0.1
3	Round	E25	10	Uncoated	450	0.2
4	Round	E25	10	Uncoated	150	0.05
5	Round	E25	10	Uncoated	300	0.1
6	Round	E25	10	Uncoated	450	0.2
7	Round	E25	100	Coated	150	0.05
8	Round	E25	100	Coated	300	0.1
9	Round	E25	100	Coated	450	0.2
10	Round	S	10	Coated	150	0.05
11	Round	S	10	Coated	300	0.1
12	Round	S	10	Coated	450	0.2
13	Round	S	100	Uncoated	150	0.1
14	Round	S	100	Uncoated	300	0.2
15	Round	S	100	Uncoated	450	0.05
16	Round	S	100	Coated	150	0.1
17	Round	S	100	Coated	300	0.2
18	Round	S	100	Coated	450	0.05
19	C-type	E25	100	Coated	150	0.1
20	C-type	E25	100	Coated	300	0.2
21	C-type	E25	100	Coated	450	0.05
22	C-type	E25	100	Uncoated	150	0.1
23	C-type	E25	100	Uncoated	300	0.2
24	C-type	E25	100	Uncoated	450	0.05
25	C-type	E25	10	Coated	150	0.2
26	C-type	E25	10	Coated	300	0.05
27	C-type	E25	10	Coated	450	0.1
28	C-type	S	100	Uncoated	150	0.2
29	C-type	S	100	Uncoated	300	0.05
30	C-type	S	100	Uncoated	450	0.1
31	C-type	S	10	Coated	150	0.2
32	C-type	S	10	Coated	300	0.05
33	C-type	S	10	Coated	450	0.1
34	C-type	S	10	Uncoated	150	0.2
35	C-type	S	10	Uncoated	300	0.05
36	C-type	S	10	Uncoated	450	0.1

3. Results and discussion

3.1. Effect of tool geometry and operating parameters

Figure 3 details the main effects plot for tool life with respect to tool geometry, cutting speed and feed rate. All 3 factors were found to have a statistically significant effect based on corresponding ANOVA calculations, with cutting speed showing the largest influence with a percentage contribution ratio (PCR) of 36.6%, while feed rate and tool geometry had more moderate PCR's of 17.3% and 11.5% respectively.

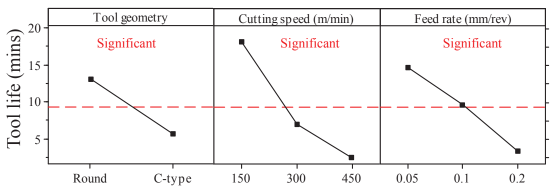

Fig. 3. Main effects plot for tool life

When turning at the lowest cutting speed (150m/min) using C-type inserts, severe grooving on the rake face and built up edge (BUE) formation similar to that shown in Fig. 4(a), was observed in all wear scar micrographs analysed, irrespective of the other parameters levels. The accumulation of BUE was thought to increase the incidence of ploughing at the expense of shearing, which led to a layer of strain hardened workpiece material that rubbed against the insert surface during machining resulting in the formation of grooves on the tools. This however was not seen when employing round shaped tools (possibly due to the larger contact area which reduced the applied stresses), with flank wear progressing gradually up to the end of life criterion, although workpiece material adhesion was still prevalent, see Fig. 4(b). This was most likely due to the tendency for chips to pressure weld onto the tool surface at low cutting speeds (high stresses with relatively low temperatures). The lack of grooving wear can be attributed to the smaller uncut chip thickness (*h*) associated with round tools compared to the C-type configuration, which is related to the feed rate (*f*) and the tool cutting edge angle (*Ø*) as detailed in Equation 1 [13]. Instances of crater wear were also observed in Tests 1 and 4.

$$h = f * \sin \phi \qquad (1)$$

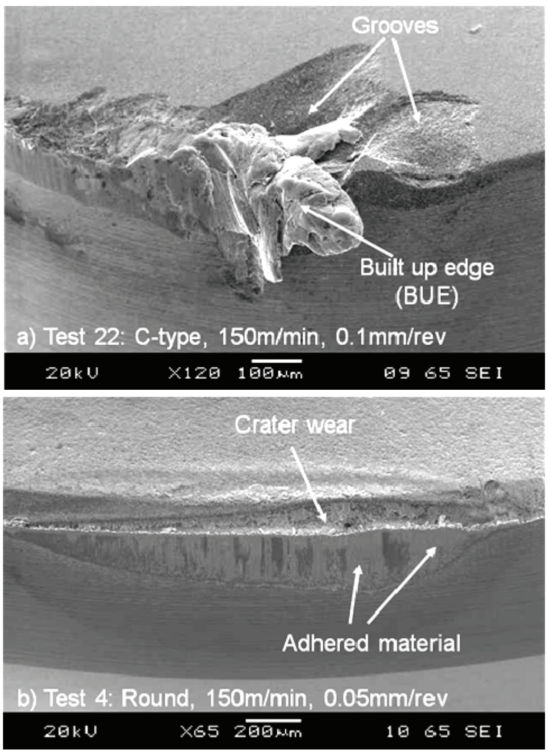

Fig. 4. SEM micrographs of worn inserts in (a) Test 22 and (b) Test 4

By only considering experiments performed at 150m/min, average tool life when utilising round inserts was ~30.7min (from Tests 1, 4, 7, 10, 13 & 16), with a maximum of 44.7mins recorded in Test 4. This was over 5 times longer than that obtained with the C-type configuration, where the average from 6 trials (based on Tests 19, 22, 25, 28, 31 & 34) was only ~5.7mins.

As cutting speed was increased to 300m/min, the presence of grooves and built up edge diminished, with the principal wear mechanism being abrasion together with small amounts of material adhesion/attrition, see Fig. 5(a) & 5(b). In contrast to the trend shown in Fig. 3, average tool life was approximately 30% higher when using C-type (~8.1mins) over round (~6.2mins) inserts, which was possibly due to the greater tool edge strength afforded by the negative rake angle geometry in the former. In addition, thrust/radial forces of up to 892N (Test 14) was recorded with the latter, which was approximately 84% higher compared to corresponding C-type tools. This was attributed to the larger tool tip radius/contact length associated with the round inserts.

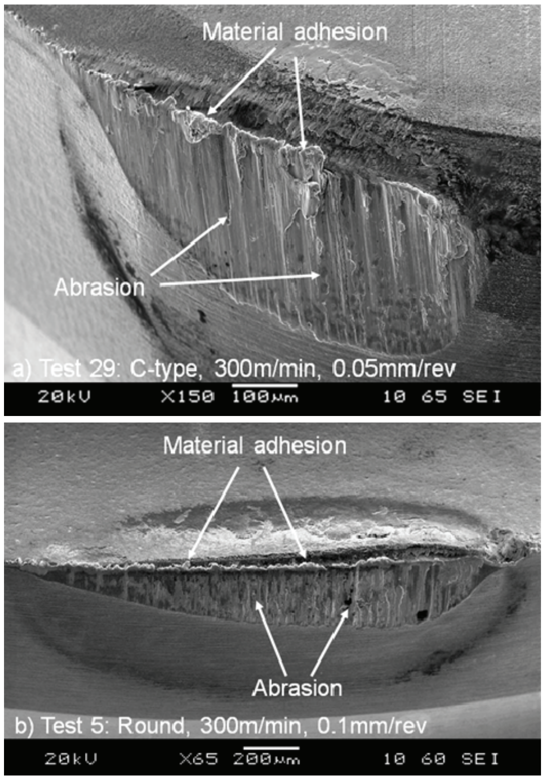

Fig. 5. SEM micrographs of worn inserts in (a) Test 29 and (b) Test 5

At the highest cutting speed of 450m/min, tool life did not exceed 3.5mins with a minimum of 1.3mins observed in Test 9. While abrasive wear marks and workpiece material adhesion were still prevalent in all tests performed, more severe wear patterns such as chipping and tool fracture were also observed particularly when operating in combination with larger feed rates of 0.1 and 0.2mm/rev, see Fig. 6(a) & 6(b).

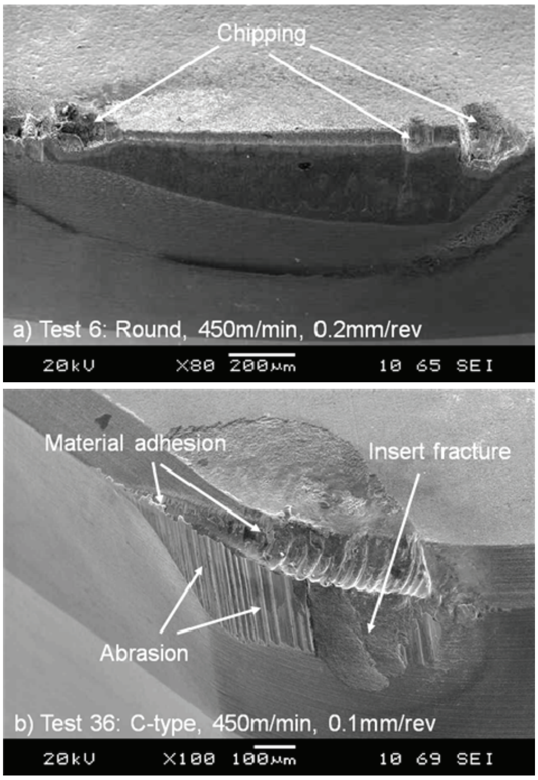

Fig. 6. SEM micrographs of worn inserts in; (a) Test 6 and (b) Test 36

Additionally, an analysis of the experiments carried out at 450m/min showed no appreciable difference in average tool life between the C-type and round inserts.

Although increasing feed rates typically led to a decrease in tool life (due to higher thermal loading and larger uncut chip thickness), certain combinations of parameters with a 0.2mm/rev feed rate were preferred (providing that inserts did not suffer catastrophic failure) in terms of productivity/material removed (cm^3). For example, ~22% higher volume of material was removed in Tests 20 & 23 after only ~6.8min compared to Test 4, which had a tool life of ~44.7min.

3.2. Influence of cutting edge preparation, cutting fluid pressure and surface condition

The variations in cutting edge preparation, fluid pressure and surface condition were found to have a minimal influence on mean tool life, see associated main effects plot in Fig. 7. Indeed, the corresponding ANOVA showed that none of the factors were statistically significant at the 5% level, with negligible PCR values. However, the experimental array/design allowed a limited assessment of the performance between the different factor levels via direct comparison of selected tests where only the parameter under consideration was varied.

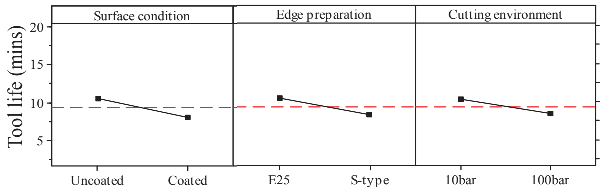

Fig. 7. Main effects plot for tool life relative to surface condition, cutting edge preparation and cutting environment/fluid pressure

In terms of tool edge preparation, data from Tests 25, 26 and 27 involving extra honed (E25) inserts were compared against those obtained in Tests 31, 32 and 33, which had chamfered and honed (S-type) peripheries, respectively. Thrust forces were consistently higher by between 30-160N when machining with the latter, despite no significant disparity in tool life between the corresponding tests. This was most likely caused by the 'blunter' S-type cutting edge and essentially a 'K-land' geometry (cutting edges with a chamfer) which increases resistance to chip flow over the tool rake face.

The difference in cutting results due to changing fluid pressure was assessed by evaluating Tests 28, 29 and 30 (100bar) with respect to Tests 34, 35 and 36 (10bar). Improvements in tool life ranging from 33-61% were observed when machining with the lower fluid pressure condition. Additionally, higher levels of force were recorded at 100bar due to the greater mechanical impact from the fluid stream, while the associated reduction in tool life was most likely the result of thermal shock (rapid heating and cooling cycles) and jet impingement (hydrodynamic) erosion. This effect was especially evident when operating at the lowest cutting speed of 150m/min. Similar findings were detailed by Ezugwu et al. [14] who reported accelerated notch wear formation when employing a higher fluid pressure of 20.3MPa as opposed to 15MPa, when turning Inconel 718 using whisker reinforced alumina ceramic tools. Furthermore, changes in chip morphology were also observed as 100bar trials generally resulted in short and discontinuous debris due to improved chip breakage provided by the high pressure fluid application, see Fig. 8(a). In contrast, cylindrical helical chips were obtained in all experiments at 10bar, which occasionally led to problems of swarf entanglement as shown in Fig. 8(b).

The effect of coatings was observed comparing Tests 19, 20 & 21 (coated) with Tests 22, 23 & 24 (uncoated) and similarly Tests 16, 17 & 18 (coated) were contrasted against Tests 13, 14 & 15 (uncoated). In general, use of coatings did not appear to provide any significant benefit in terms of tool life, which suggests that the selected composition may not have been suitable for the conditions tested. Thrust forces however were generally lower when using coated over uncoated tools.

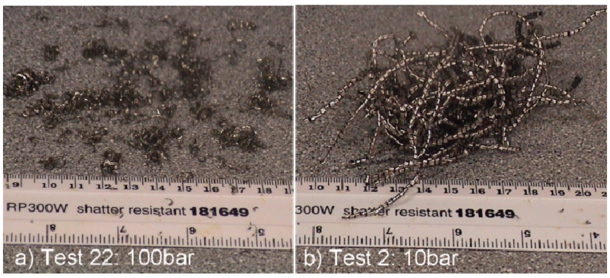

Fig. 8. Chip morphology at; (a) 100bar and (b) 10bar fluid pressure

4. Conclusions

- Flank wear was the dominant wear mode in the majority of tests as a result of abrasion, while workpiece material adhesion was similarly prominent. Severe grooving and BUE was present with tests involving C-type inserts at 150m/min, while at the highest cutting speed of 450m/min, insert fracture, chipping and thermal cracks were observed.
- Round shaped inserts significantly outperformed the rhomboid/C-type tools in terms of tool life at low cutting speeds, however there was no major difference between the two geometries when operating at the higher parameters of 300 and 450m/min.
- The main effects plots pointed to the use of uncoated, round inserts with an E25 cutting edge preparation at a cutting speed of 150m/min, feed rate of 0.05mm/rev and 10bar fluid pressure in order to achieve the longest tool life. These conditions however gave relatively low levels of productivity/material removal rate and alternative parameter combinations involving the intermediate cutting speed and high feed rate of 300m/min and 0.2mm/rev respectively, were found to be preferable.
- ANOVA calculations showed that cutting speed, feed rate and tool geometry had a significant effect on tool life with corresponding PCR's of 36.6%, 17.3% and 11.5% respectively. Although not a statistically significant factor, the use of high pressure fluid (100bar) was occasionally detrimental to tool life, particularly at low cutting speeds.

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